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Noncovalent Encapsulation of Cobaltocenium inside Resorcinarene Molecular Capsules

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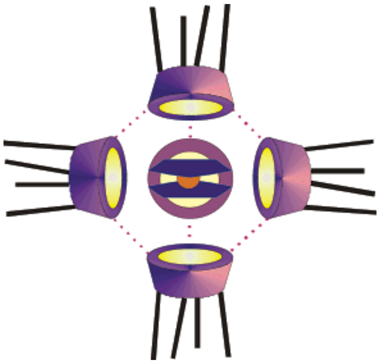

The encapsulation of cobaltocenium (Cob^+) inside hexameric molecular capsules of two different resorcinarenes was investigated in dichloromethane solution. Both ^1H NMR spectroscopic and voltammetric experiments clearly reveal that Cob^+ experiences encapsulation. Diffusion coefficient measurements obtained from PGSE NMR experiments indicate that the molecular capsules exist in dichloromethane solution in the absence of any cations. Bound and free Cob^+ ions undergo slow exchange on the NMR time scale, but the bound Cob^+ ions rotate and/or tumble freely inside the molecular capsules. Under experimental conditions suitable for voltammetry the encapsulation of Cob^+ depends on the nature of the supporting electrolyte. Tetraalkylammonium hexafluorophosphate, tetrafluoroborate, and perchlorate supporting electrolytes prevent the encapsulation of Cob^+, while tetraalkylammonium chloride and bromide salts allow it. The nature of the tetraalkylammonium cation plays a smaller role in the encapsulation. Finally, the structure of the resorcinarene also factors into the overall stability of the molecular assembly.

Introduction

Resorcinarenes are well-known tetrameric macrocyclic octols prepared by the acid condensation of resorcinol in the presence of an aldehyde.[1] Although these compounds have been often used in supramolecular chemistry,[2] they are now attracting considerable attention as components of molecular capsules. In a seminal report published in 1997, MacGillivray and Atwood crystallized a fascinating molecular capsule formed by the self-assembly of six resorcinarene molecules.[3] The six resorcinarenes and eight water molecules were held together in a snug cube configuration by a network of sixty hydrogen bonds. A very interesting aspect of these molecular assemblies is their large size, with an internal estimated volume of 1375 Å^3. The molecular capsule reported by MacGillivray and Atwood was formed by compound **1** (see Figure 1 for the structures) and investigated in the solid state by X-ray diffraction techniques. Its possible existence in solution was not clearly substantiated at that time. Three years ago, Shivanyuk and Rebek published NMR spectroscopic evidence consistent with the self-assembly of hexameric capsules of resorcinarene **2** around a number of cationic species in chloroform solution (saturated with water).[4] The groups of Rebek[5] and Atwood,[6] as well as Avram and Cohen,[7] have investigated extensively these

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[1] Tunstad, L. M.; Tucker, J. A.; Dalcanale, E.; Weiser, J.; Bryant, J. A.; Sherman, J. C.; Helgeson, R. C.; Knobler, C. B.; Cram, D. J. *J. Org. Chem.* **1989**, *54*, 1305.

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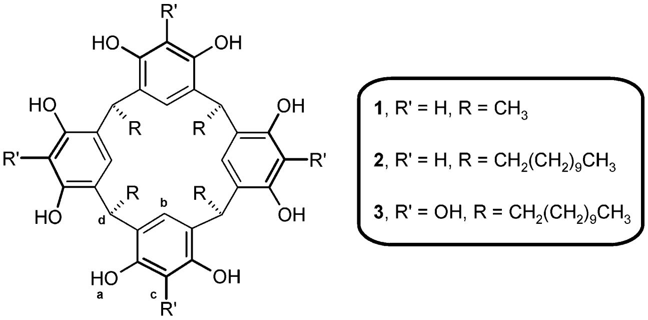

FIGURE 1. Relevant resorcinarene structures.

molecular capsules using ^{1}H NMR spectroscopy as their primary tool. The self-assembly of a resorcinarene structurally similar to **3** into a molecular capsule was first reported by Mattay and co-workers.[8]

We were inspired by the initial findings in this area and intrigued by the effects of noncovalent encapsulation on the heterogeneous electron-transfer reactions of redox-active guests. Therefore, we started work on the potential encapsulation of cobaltocenium by hexameric molecular capsules of resorcinarenes. Bis(cyclopentadienyl)cobalt(III) or cobaltocenium (Cob$^+$) is a highly stable, 18-electron complex which is isoelectronic with its iron(II) analogue, ferrocene. Cobaltocenium bears one positive charge and can be reversibly reduced to its neutral form, cobaltocene (Cob). We wanted to explore the effects that the redox conversions of this organometallic compound may have on the self-assembly of resorcinarenes in solution. For a number of years, we have also been interested in the electrochemical behavior of encapsulated redox centers,[9] and resorcinarene molecular capsules appeared to offer a novel and convenient method to prepare encapsulated electroactive centers. We reported some preliminary results of this investigation recently.[10] In this paper, we offer a more complete account of the experimental results of this work, while the interest in these systems seems to increase at a fast pace.

Results and Discussion

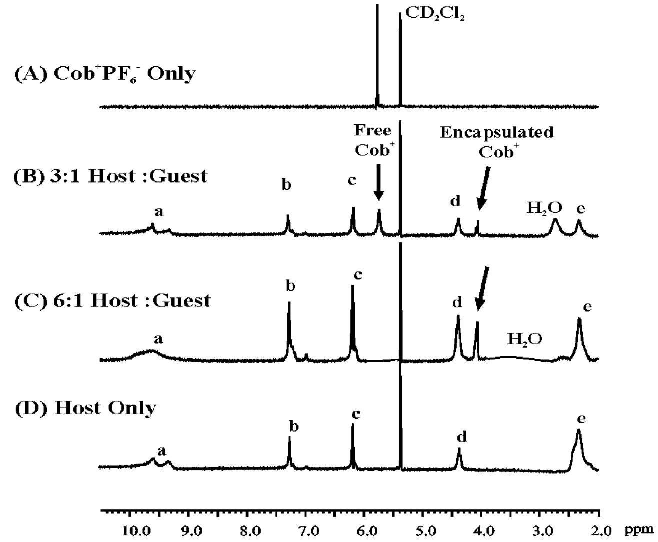

FIGURE 2. ^{1}H NMR (400 MHz) spectra of Cob$^+$PF$_6^-$ and host **2** in CD$_2$Cl$_2$.

Encapsulation of Cobaltocenium inside 2$_6$ Capsules. The encapsulation of cobaltocenium by resorcinarene **2** can be readily monitored by ^{1}H NMR spectroscopy in CD$_2$Cl$_2$ solution. In this medium, Cob$^+$ (as its hexafluorophosphate salt) exhibits a singlet resonance corresponding to its 10 equivalent protons which appears at 5.64 ppm (Figure 2A). Upon addition of compound **2**, a second resonance for the Cob$^+$ protons is visible at 4.03 ppm. Figure 2B shows the spectrum recorded when 3.0 equiv of **2** is present. As the concentration of **2** increases so does the intensity of the signal at 4.03 ppm, while the intensity of the original Cob$^+$ signal decreases. The growth of the resonance at 4.03 ppm is always at the expense of the signal at 5.64 ppm. The simultaneous observation of these two signals clearly reveals that they correspond to the protons of free and bound Cob$^+$, which are engaged in a process of slow exchange (in relation to the corresponding NMR time scale). What is the nature of the bound Cob$^+$ species? Key information on the stoichiometry of the bound species derives from the experimental observation that the free Cob$^+$ signal disappears upon the addition of exactly 6 equiv of resorcinarene **2**, a point at which the bound Cob$^+$ signal reaches full development (Figure 2C). These NMR spectroscopic results are very reminiscent of the findings reported by Shivanyuk and Rebek with redox-inactive cations in chloroform solution.[4] Therefore, we conclude that cobaltocenium is sequestered inside a molecular capsule formed by six molecules of resorcinarene **2**. Furthermore, the observation of a broad singlet for the Cob$^+$ protons inside **2**$_6$ reveals that the organometallic cation is free to rotate inside the hexameric molecular capsule.

At this juncture, we decided to take advantage of pulse gradient stimulated echo (PGSE) NMR techniques to investigate the diffusion of these molecules in solution.[7c,11] The advantages offered by this technique for the determination of diffusion coefficients (D_0) have been well documented.[12] Using PGSE NMR, the diffusion coef-

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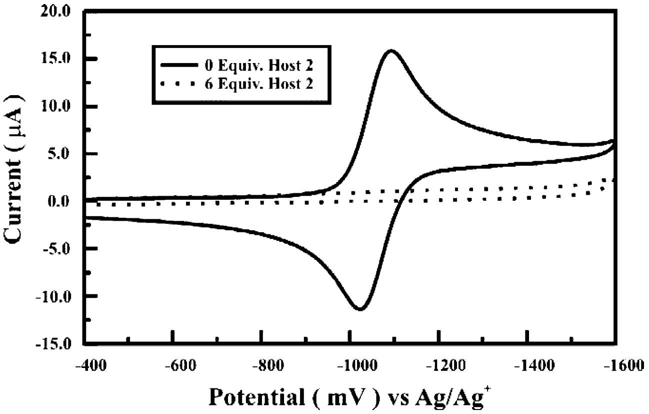

FIGURE 3. Cyclic voltammetric behavior on glassy carbon (0.071 cm^2) of 1.0 mM Cob$^+$PF$_6^-$ in CH$_2$Cl$_2$ also containing 0.1 M tetradodecylammonium bromide: solid line, no host **2** present; dotted line, in the presence of 6.0 mM **2**. Scan rate 0.1 V/s.

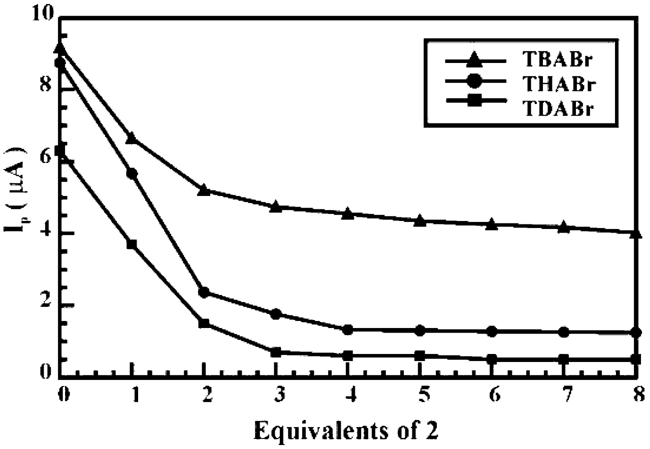

FIGURE 4. Cathodic peak currents measured (0.1 V/s, 0.072 cm^2 glassy carbon) for the reduction of 1.0 mM Cob$^+$ in the presence of variable concentrations of host **2** and 0.2 M TBABr, THABr, or TDABr in CH$_2$Cl$_2$ solution.

ficient for Cob$^+$ was determined to be 1.7 × 10^{-5} cm^2/s. In a separate experiment the D_0 value for resorcinarene **2** was measured as 3.0 × 10^{-6} cm^2/s, which is clearly lower than what would be expected for a molecule of this size (MW = 1104) freely diffusing in a low-viscosity solvent, such as CD$_2$Cl$_2$. In fact, our D_0 value is essentially identical to that reported by Avram and Cohen[7] for the hexameric molecular capsule of **2** in CDCl$_3$ after the different solvent viscosities are taken into account. The diffusion coefficients of Cob$^+$ and **2** were also determined in a solution containing 1 equiv of Cob$^+$ and 6 equiv of **2**. In this case, both diffusion coefficients turned out to be identical (3.0 × 10^{-6} cm^2/s), which reveals the strong association of the cobaltocenium cation with the resorcinarenes. Furthermore, the diffusion coefficient of **2** is unaffected by the presence of Cob$^+$, indicating that *the association of the resorcinarene into molecular capsules takes place in the absence of any cations in solution*. This finding is in excellent agreement with a number of experimental results recently reported by other groups[5,7] which were obtained with the same resorcinarene in deuterated chloroform solution. Clearly, all these data dispel the notion that cations may be required as "seeds" in the self-assembly of resorcinarenes, such as **2**. Our experimental data are consistent with molecular capsule formation in CD$_2$Cl$_2$ solutions in the absence of any cation. On the other hand, our data also indicate that the addition of cobaltocenium cations to a solution of resorcinarene **2** leads to their rapid encapsulation, which reveals two things: (1) the replacement of solvent molecules by cobaltocenium in the interior of the capsules is thermodynamically favored, and (2) the capsules show enough kinetic lability to allow the rapid incorporation of the Cob$^+$ cations.

Can we detect this encapsulation process using electrochemical techniques? The cathodic voltammetric behavior of Cob$^+$ in CH$_2$Cl$_2$ solution is shown in Figure 3. As expected, the cyclic voltammogram shows a completely reversible wave at a half-wave potential of −1.06 V vs Ag$^+$/Ag corresponding to the Cob$^+$/Cob redox couple. The current associated with this wave decreases as resorcinarene **2** is added to the solution. Figure 3 also presents the cyclic voltammogram obtained upon the addition of 6 equiv of **2**, at which point the wave associated with the Cob$^+$/Cob redox couple is no longer observed.

We also performed control experiments in which **2** was added to solutions containing cobaltocenium and decamethylferrocene. Under these conditions, the addition of **2** had the same effect on the Cob$^+$/Cob wave, but the wave corresponding to the reversible oxidation of decamethylferrocene only suffers minimal potential shifts in the presence of resorcinarene.[10] This finding demonstrates that the loss of electrochemical response from Cob$^+$ is not due to any passivation of the working electrode surface, since the electrochemical oxidation of decamethylferrocene was not affected. In fact, the observed electrochemical behavior is certainly consistent with the complete encapsulation of Cob$^+$.

To assess the nature of the surrounding molecular capsule, we titrated a 1.0 mM solution of Cob$^+$ (in CH$_2$Cl$_2$ also containing 0.2 M tetradodecylammonium bromide) with increasing amounts of host **2**. Surprisingly, the voltammetric wave corresponding to the redox couple Cob$^+$/Cob disappears completely after the addition of 3 equiv of **2**. Beyond this point, no electrochemical response for Cob$^+$ was detected with increasing concentrations of **2** (see Figure 4). These results suggest that, *under the conditions of the electrochemical experiments, dimeric or trimeric capsules may form around the organometallic cation*. The literature contains some precedents of self-assembled capsules formed by less than six resorcinarenes.[13] If Cob$^+$ is sequestered inside a capsule formed by two or more molecules of resorcinarene **2**, we would anticipate that its voltammetric behavior would be strongly affected, given the fact that the distance of maximum approach between Cob$^+$ and the electrode surface increases substantially upon encapsulation. In other words, encapsulation displaces the location of the outer Helmholtz plane (OHP) for the reduction of Cob$^+$ further away from the electrode surface, leading to

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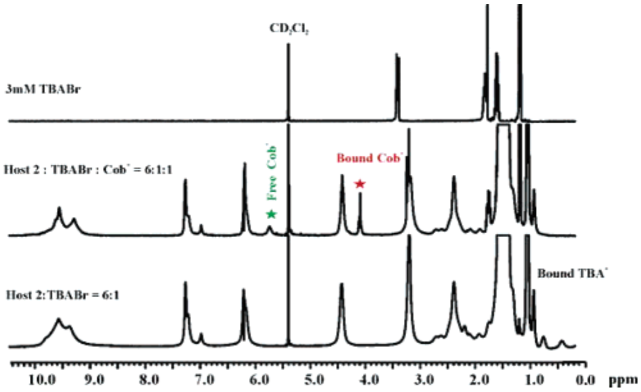

FIGURE 5. ^{1}H NMR spectra (400 MHz, CD$_2$Cl$_2$) of (top) 3 mM TBABr, (middle) 6 mM **2**, 1 mM (Cob)PF$_6$, and 1 mM TBABr, and (bottom) 6 mM **2** and 1 mM TBABr.

considerably slower electrochemical kinetics, which is consistent with the voltammetric results shown in Figure 3. The literature contains some precedents of encapsulation of redox-active centers by covalent or noncovalent means.[9] Very often, encapsulation leads to decreased rates of heterogeneous electron transfer, in general agreement with our results.[9b]

Effects of the supporting electrolyte. The electrochemical results shown in Figure 3 were obtained using tetradodecylammonium bromide (TDA$^+$Br$^-$) as the supporting electrolyte. The selection of this supporting electrolyte was the result of a good number of electrochemical experiments in search of optimum conditions for the encapsulation. From the start of this work we were concerned with the possible competition for the interior volume of the molecular capsules between cobaltocenium ions and the tetraalkylammonium cations of the supporting electrolytes commonly used in organic solvents, such as dichloromethane. Our experiments demonstrate that the supporting electrolyte anions play a somewhat unexpected and more important role than the cation. In fact, we performed experiments under conditions similar to those of Figure 3 with tetrabutylammonium bromide (TBA$^+$Br$^-$), tetrahexylammonium bromide (THA$^+$Br$^-$), and TDA$^+$Br$^-$ as supporting electrolytes. In all cases, the encapsulation of Cob$^+$ was very similar and complete or close to complete in the presence of 6 equiv of resorcinarene **2**. Only a small difference was detected in the case of TBA$^+$Br$^-$, as a residual wave for the Cob$^+$/Cob redox couple was observed (see the Supporting Information). Similar results were obtained in the titration experiments shown in Figure 4.

Intrigued by the strong preference for Cob$^+$ versus tetraalkylammonium cations shown by resorcinarene capsules in voltammetric experiments, we decided to test this selectivity using ^{1}H NMR experiments. The results are shown in Figure 5. The key observation is that the encapsulation of 1 equiv of Cob$^+$ by 6 equiv of resorcinarene **2** is not complete in the presence of 1 equiv of TBA$^+$, as revealed by the residual peak corresponding to free Cob$^+$ in the middle spectrum of Figure 5. This residual unbound Cob$^+$ resonance is not observed in the absence of TBA$^+$ (Figure 2). However, this spectrum clearly reveals the selectivity of **2**$_6$ capsules for Cob$^+$, since signals for encapsulated TBA$^+$ (at δ < 1.0 ppm) are essentially undetectable when TBA$^+$ and Cob$^+$ compete for the interior of the capsule.

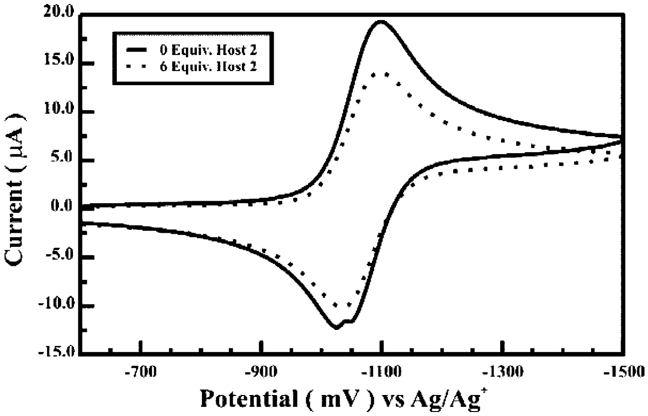

FIGURE 6. Cyclic voltammetric behavior on glassy carbon (0.071 cm^2) of 1.0 mM Cob$^+$PF$_6$$^-$ in CH$_2$Cl$_2$ also containing 0.1 M tetradodecylammonium hexafluorophosphate: solid line, no host **2** present; dotted line, in the presence of 6.0 mM **2**. Scan rate 0.1 V/s.

At this juncture we must point out that there are some considerable differences between the conditions for our electrochemical and NMR spectroscopic experiments. First, we always employ cobaltocenium in its commercially available form, which is the hexafluorophosphate salt. In the NMR experiments, no supporting electrolyte is needed, so the PF$_6$$^-$ concentration is small (in the millimolar range) and equal to the concentration of Cob$^+$. In the electrochemical experiments, we used ~1 mM Cob$^+$PF$_6$$^-$, but we added at least a 100-fold excess of supporting electrolyte (~0.1−0.2 M), as required to decrease the resistivity of the solution and to minimize mass transfer of the electroactive Cob$^+$ ions by migration. Therefore, the nature of the supporting electrolyte becomes extremely important because its concentration is about 100 times higher than that of the electroactive Cob$^+$ ion. The fact that the supporting electrolyte cation has a small effect on the recorded voltammetric behavior of Cob$^+$ when **2** is present reveals that *cobaltocenium has a much greater affinity for the interior of the molecular capsules than any of the tetraalkylammonium cations surveyed here in the presence of bromide or chloride counterions*.

The nature of the anion turned out to be much more relevant for the type of voltammetric behavior observed. Using TBA$^+$Br$^-$, THA$^+$Br$^-$, TDA$^+$Br$^-$, and TBA$^+$Cl$^-$ as supporting electrolytes, we observed no voltammetric response (or a very small residual wave) in the presence of 6 equiv of host **2**. In fact, our voltammetric titration results (Figure 4) strongly indicate that encapsulation of Cob$^+$ is essentially complete upon addition of 2−3 equiv of **2** when using THA$^+$Br$^-$ and TDA$^+$Br$^-$ supporting electrolytes. By contrast, if TBA$^+$PF$_6$$^-$, TDA$^+PF_6$$^-$, TBA$^+ClO_4$$^-$, or TBA$^+BF_4$$^-$ is used as supporting electrolyte, the voltammetric response of the Cob$^+$/Cob couple is little affected by the resorcinarene, showing only very minor current and half-wave potential changes (see Figure 6). Clearly, Br$^-$ and Cl$^-$ favor the encapsulation, while in the presence of excess PF$_6$$^-$, BF$_4$$^-$, and ClO$_4$$^-$ cobaltocenium is not encapsulated inside the **2**$_6$ molecular capsules. This finding suggests that ion pairing effects between these anions and Cob^+ and the tetraalkylammonium cations may play an important role and, perhaps, decrease the affinity of Cob^+ for the inside of the molecular capsules. Furthermore, incorporation of Br^- and Cl^- into the networks of hydrogen bonds that keep the capsules together may also be playing an important role.

Intrigued by the effects of Br^- on the structure of the molecular capsules formed by host **2**, we performed ^1H NMR titrations of this host with increasing concentrations of TBA^+Br^-. The addition of even small concentrations (1/6 equiv) of TBA^+Br^- considerably broadens the proton resonances of the host. Upon addition of 2−4 equiv of TBA^+Br^- a new set of signals appears for host **2**. The new set of proton resonances becomes more intense at the expense of the original set of **2** resonances with increasing TBA^+Br^- concentration. Finally, at ca. 10 equiv of TBA^+Br^-, the conversion is complete and the original set of resonances disappears. At low concentrations of TBA^+Br^- (under 4 equiv), peaks corresponding to encapsulated TBA^+ are observed at $\delta < 1.0$ ppm. However, these peaks are no longer detected as the new set of resonances for host **2** starts to predominate (4−10 equiv). PGSE NMR measurements with this new set of proton resonances of host **2** afford a diffusion coefficient value of 5×10^{-6} cm^2/s, which is larger than the diffusion coefficient of the $\mathbf{2}_6$ capsule (3.0×10^{-6} cm^2/s) in CD_2Cl_2 solution. The new peaks are also sharper than the original ones. Furthermore, similar titration experiments with $TBA^+PF_6^-$ reveal some encapsulation of TBA^+, but the proton resonances for the $\mathbf{2}_6$ capsule are not affected at all. These findings indicate that the $\mathbf{2}_6$ molecular capsule is strongly affected by the presence of bromide, which may engage in hydrogen bonding with the resorcinarene hydroxyl groups, disrupting the molecular capsules and preventing the encapsulation of TBA^+. Similar results in $CDCl_3$ solution have been reported by the Rebek[5a] and Cohen[7e] groups. In contrast to these findings, our electrochemical data reveal encapsulation of Cob^+ in the presence of the much larger concentrations of tetraalkylammonium bromide supporting electrolytes utilized in the voltammetric experiments, although the stoichiometry does not agree with the usual hexameric resorcinarene capsules. Again, this underscores the differences in the experimental conditions required for voltammetric and ^1H NMR spectroscopic experiments.

Encapsulation of Cobaltocenium Inside $\mathbf{3}_6$ Capsules. Resorcinarene **3** has four more hydroxyl groups on the upper rim than resorcinarene **2**. The ability of this resorcinarene to form $\mathbf{3}_6$ molecular capsules stabilized by a larger number of hydrogen bonds than in $\mathbf{2}_6$ suggests that this resorcinarene may give rise to very robust self-assembled structures.[7a,8] Therefore, we investigated the encapsulation of cobaltocenium by **3** to establish a comparison between the two resorcinarenes. We first ran ^1H NMR spectroscopic experiments, which quickly revealed some differences between the two hosts. Unlike that of host **2**, the presence of 6 equiv of **3** does not lead to the complete encapsulation of Cob^+ (see Figure 7). This finding does not imply that $\mathbf{3}_6$ capsules are less stable than $\mathbf{2}_6$ capsules. These experiments do not provide a direct measurement of the stability of the capsules, but they rather reflect the affinity of the Cob^+ cation for the inner space of the molecular capsules in CD_2Cl_2 solution.

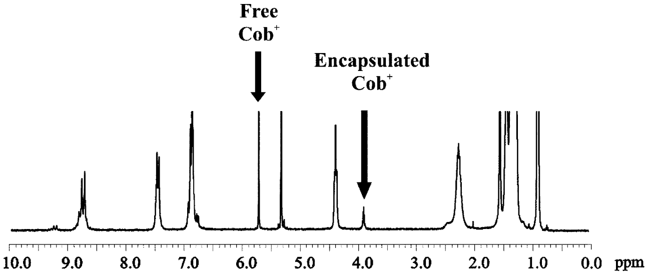

FIGURE 7. ^1H NMR spectrum (400 MHz, CD_2Cl_2) of a solution containing 0.5 mM $Cob^+PF_6^-$ and 3.0 mM host **3**.

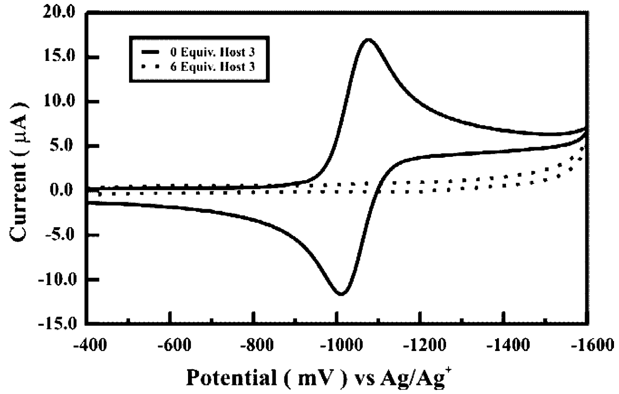

FIGURE 8. Cyclic voltammetric behavior on glassy carbon (0.071 cm^2) of 1.0 mM $Cob^+PF_6^-$ in CH_2Cl_2 also containing 0.1 M tetradodecylammonium bromide: solid line, no host **3** present; dotted line, in the presence of 6.0 mM **3**. Scan rate 0.1 V/s.

In other words, the results of these experiments reveal the lower relative stability of $Cob^+@\mathbf{3}_6$ compared to $Cob^+@\mathbf{2}_6$, which is consistent with the recent findings of Avram and Cohen.[7b]

We also performed ^1H NMR PGSE experiments to determine the diffusion coefficients of the species involved. The diffusion coefficient of host **3** in CD_2Cl_2 was determined to be 3.7×10^{-6} cm^2/s, which is slightly larger than the value obtained for host **2**. Furthermore, the diffusion coefficient of **3** does not change much in the presence of Cob^+ (3.6×10^{-6} cm^2/s), and a similar value is also obtained from the encapsulated Cob^+ proton signal at 3.9 ppm (3.5×10^{-6} cm^2/s). Once again, the similarity in the diffusion coefficient values obtained using the guest (Cob^+) and the host proton signals supports the existence of a stable assembly composed of the resorcinarene $\mathbf{3}_6$ capsule and the included cationic guest. In this case, the observation of a Cob^+ proton signal outside the capsule allows us to determine the corresponding diffusion coefficient, which was found to be 1.0×10^{-5} cm^2/s. This value is lower than that obtained for free Cob^+ (vide supra), suggesting that the outside Cob^+ species might be interacting with the capsule or some of its components.

Our electrochemical data clearly indicate that **3** is capable of forming molecular capsules around Cob^+. With 0.1 M TDA^+Br^- as the supporting electrolyte, the voltammetric response of Cob^+ is essentially eliminated by the presence of 6 equiv of **3** (Figure 8), a result which is consistent with the incorporation of Cob^+ inside $\mathbf{3}_6$ molecular capsules, leading to a considerable increase in

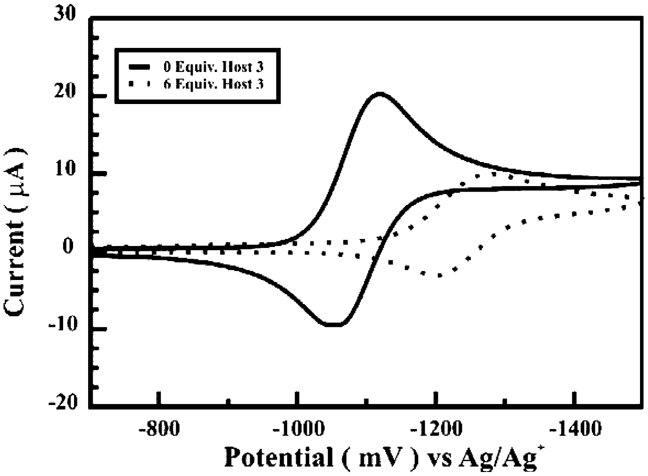

FIGURE 9. Cyclic voltammetric behavior on glassy carbon (0.071 cm^2) of 1.0 mM Cob$^+$PF$_6$$^-$ in CH$_2$Cl$_2$ also containing 0.1 M tetrabutylammonium bromide: solid line, no host **3** present; dotted line, in the presence of 6.0 mM **3**. Scan rate 0.1 V/s.

the distance between the effective OHP and the electrode surface and a subsequent decrease in the rate of heterogeneous electron transfer.

While this experimental result does not allow us to establish a comparison between **2** and **3**, the voltammetric behavior of Cob$^+$ with other supporting electrolytes showed clear differences between the two resorcinarenes. Most remarkably, using 0.1 M TBA$^+$Br$^-$ as the supporting electrolyte, the presence of 6 equiv of host **3** leads to a considerable decrease of the observed Cob$^+$/Cob current levels and a cathodic shift of the half-wave potential for this redox couple (Figure 9). Clearly, the voltammetric data do not support complete encapsulation of Cob$^+$ in this case. The electrochemical parameters observed are consistent with a large fraction of Cob$^+$ ions interacting with resorcinarene hosts, perhaps forming complexes in which each Cob$^+$ is at best only partially encapsulated by one or two molecules of **3**. The use of THA$^+$Br$^-$ as supporting electrolyte results in voltammetric results intermediate between those observed with TDA$^+$Br$^-$ and TBA$^+$Br$^-$. Voltammetric titration experiments similar to those shown in Figure 4 also suggest that complete encapsulation of Cob$^+$ is achieved with 3−4 equiv of **3** when using TDA$^+$Br$^-$. However, complete encapsulation is not attained with THA$^+$Br$^-$ and TBA$^+$Br$^-$ supporting electrolytes even upon addition of even 7 equiv of host **3** (Supporting Information). In the case of resorcinarene **3**, the extent of Cob$^+$ encapsulation observed under voltammetric conditions increases in the order TBA$^+$ < THA$^+$ < TDA$^+$, while this trend is less detectable when using **2** as the building block for the molecular capsules. Therefore, we must conclude that Cob$^+$ has less affinity for the inner space of the **3**$_n$ molecular capsules than for that within the **2**$_n$ molecular capsules. It is important to point out here that these experimental results do not reflect the inherent stability of the two hexameric molecular capsules. They rather reflect their relative stabilities when filled by cobaltocenium.

To gauge the relative stabilities of the capsules formed by either resorcinarene, we performed a series of voltammetric experiments with TDA$^+$Br$^-$, a supporting electrolyte which favors the encapsulation of Cob$^+$ since the TDA$^+$ cation is too large to fill the inner space of the capsules. More specifically, we added DMSO to the solution to assess the relative stability of the capsules. This solvent competes effectively for hydrogen-bonding sites and is routinely utilized to disrupt hydrogen-bonded assemblies. Our experimental data suggest that Cob$^+$@**2**$_n$ capsules are more easily disrupted by DMSO than Cob$^+$@**3**$_n$ capsules (Figure 10). Notice that the presence of ca. 13% (v/v) DMSO leads to the full development of the cathodic voltammetric wave of Cob$^+$, which represents the complete disruption of the Cob$^+$@**2**$_n$ molecular capsule, while a much larger proportion of DMSO (27% v/v) is required to reach a similar level of disruption with Cob$^+$@**3**$_n$ molecular capsules. This reflects the larger number of hydrogen bonds holding together **3**$_n$ as compared to **2**$_n$, which translates into a higher intrinsic stability for the former capsule assembly. Overall, **3**$_n$ capsules are more robust than **2**$_n$ capsules, but the Cob$^+$ cation has more affinity for the interior of the latter capsules, in general agreement with the findings of Avram and Cohen.[7b]

In conclusion, our NMR spectroscopic and voltammetric results demonstrate that stable hexameric molecular capsules of resorcinarenes **2** and **3** are formed in dichloromethane solution. The formation of these capsules takes place in the absence of cationic seeds, but Cob$^+$ ions are easily and efficiently incorporated inside the capsules. Cob$^+$ ions compete quite effectively with tetraalkylammonium cations for the interior phase of the capsules, but cation preferences by the molecular capsules are strongly affected by the nature of the supporting electrolyte in electrochemical experiments, as well as by the structure of the resorcinarene. Overall, these results

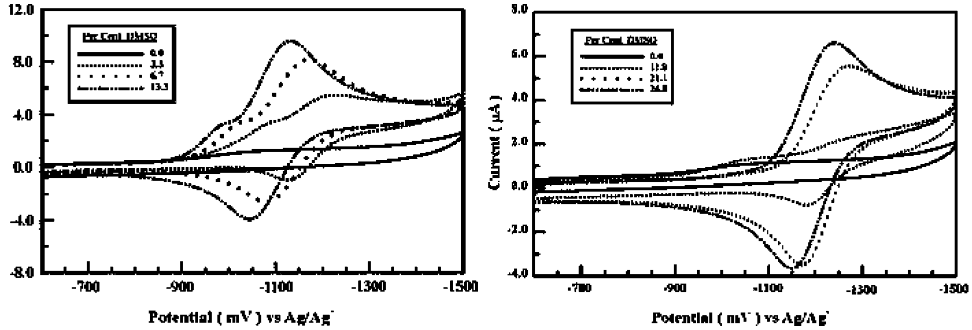

FIGURE 10. Cyclic voltammetric behavior on glassy carbon of 1.0 mM CobPF$_6$ + 6.0 mM **2** (left) or 6.0 mM **3** (right) CH$_2$Cl$_2$ solutions also containing 0.1 M TDABr and variable concentrations of DMSO. Scan rate 0.1 V/s.

highlight the complexity of the phenomena responsible for the formation of these molecular capsules and underscore the delicate balance among hydrogen-bonding, cation−π, and ion pairing interactions responsible for this molecular self-assembly process.

Experimental Section

Materials. Resorcinarenes **1**−**3** were prepared following published procedures.[1] Tetradodecylammonium bromide was prepared by the treatment of tridodecylamine with bromododecane. All other tetraalkylammonium salts were commercially available, and subject to counterion exchange when necessary. Cobaltocenium hexafluorophosphate was purchased from a commercial supplier and used as received. Deuterated solvents for NMR spectroscopy were supplied commercially. Absolutely no effort was made to dry or keep dry the dichloromethane (deuterated or not) used in our experiments. Thus, both CH_2Cl_2 and CD_2Cl_2 solutions were equilibrated with the laboratory atmosphere in terms of moisture content. We performed control electrochemical and ^{1}H NMR spectroscopic experiments with solutions prepared with water-saturated dichloromethane and obtained results identical to those reported here.

NMR Spectroscopic Experiments. ^{1}H NMR spectra were obtained at 400 MHz. As described before the CD_2Cl_2 used for sample preparation was equilibrated with the laboratory atmosphere. For the PGSE experiments, the rectangular gradient pulse length (δ) and delay between gradient pulses (Δ) were 4 and 54 ms, respectively. All spectra were recorded on a spectrometer equipped with a GAB z-gradient unit capable of producing magnetic pulsed field gradients in the z-direction up to 0.50 T/m.

Electrochemical Experiments. A glassy carbon disk working electrode (0.071 cm^2), a platinum wire counter electrode, and a nonaqueous Ag/Ag$^+$ reference electrode were fitted to a single-compartment cell for the voltammetric experiments. No attempt was made to dry the dichloromethane used for solution preparation. The solution was deoxygenated by purging with nitrogen gas and maintained under an inert atmosphere for the duration of the electrochemical experiments.

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Supporting Information Available: Additional voltammetric data as mentioned in the text (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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